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9 Non-Intrusive System Control of FACTS

For the implementation of FACTS-Devices, especially for controllable transmission paths in an AC-system, intensive planning studies and redesign of control and protection systems have to be executed. Adverse control interactions with other controllers and a lack of optimization potential due to predefined devices have to be considered. Applying a control architecture, which enables the operation of a new FACTS-device and especially a controlled transmission path without affecting the rest of the system, can eliminate these problems. This non-intrusiveness is the key issue of the so-called Non-Intrusive System Control (NISC) architecture. In this chapter the basic requirements and structure of this new control architecture are described first. A second focus is given to the problem of controller interactions in abnormal operation situations where the NISC architecture helps to avoid malfunctioning or adverse reactions.

9.1 Requirement Specification

Power system control analysis and design methodologies are mainly aiming at the assessment of single devices by means of their systemic behavior. In particular in the area of devices enhancing the flexibility of power systems (FACTS-devices) the corresponding design techniques are dedicated to either steady-state operation or power system dynamic improvement. In the spot of application studies normally FACTS-devices are considered as stand-alone solutions. These approaches are limited to a given device functionality rather than considering and designing the entire system on functional basis. The design of a solution for a transmission problem by starting from a functional specification offers more degrees of freedom. Herein, impedance control, voltage and current injection are considered as single functions. However, this design process demands a corresponding portfolio of modularized components comprising switched elements as well as power electronic subsystems. The device requirements as a result of the design process needs to be mapped to select the specific FACTS-devices out of the available portfolio.

Beyond these hardware related issues the design of a proper control and system integration methodology is needed. Most of the known approaches demand to consider the entire system, i.e. detailed knowledge of the structure and parameters of all other network components is mandatory for the design process. This is not only related to a huge effort during the design phase but also more and more limited due to the deregulation. Since transmission as such becomes a competitive in-

strument the availability of planning data cannot basically be assured. Especially for congested transmission paths between utility or country borders it is hard to get complete system planning data for the entire system.

Furthermore, the design methods may yield a complete set of new parameters for all controllers of the entire system. Both, new controlled and uncontrolled AC-transmission paths will always affect the dynamics and behavior of the rest of system. In conclusion, it is mandatory to provide a system behavior that is not inadvertently affecting the entire system. Exceptions are related to the provision of certain control functions as ancillary services.

The proposed control architecture, called Non-Intrusive System Control (NISC) avoids complete system redesign. It enables a most effective system expansion and more effective network utilization by considering the needed transmission functions first. In a second step the hardware modules are assembled accordingly. The goal of the NISC-architecture is to simplify the design process so that the new controlled transmission paths can be designed without extensive system studies. For the operation of a new transmission path the NISC-architecture avoids adverse control interactions within the entire system without causing a redesign of already implemented controllers. Those are automatic voltage regulators, power system stabilizers etc. Additionally, the proposed architecture allows for a proper reaction on critical events and avoids insufficient and hence wrong operation after the power system state changes. Both, normal and abnormal operation situations are considered at the same time. In contrast, if the entire control systems would have been designed according to global parameterization for a fixed topology mal-operations and adverse control interactions may occur [1], [2].

After describing the general approach of NISC, the different aspects of the NISC design methodology are discussed to more detailed extend in the following.

9.1.1 Modularized Network Controllers

The expansion of an electric power network means adding a new part to the system or upgrading an existing part for the transmission of electric power. Mostly this is limited to a connection of two points of a given network or between two networks (included are also 3 point connections or the interconnection of a new independent power producer). If this connection is supposed to be controllable or the controllability of a given transmission system is suggested to certain extensions, transformer based, especially phase shifter, or power electronic based sub-systems are installed. In particular the latter ones are integrated into the system to enable power flow control, reactive power compensation or ancillary services like damping of oscillations. Ideally, a controllable transmission line can be modeled as a system comprising sending end, receiving end and an intermediate coupling. In the ideal case both ends show a decoupled behavior. Figure 9.1 shows the principle structure of such a transmission interconnection.

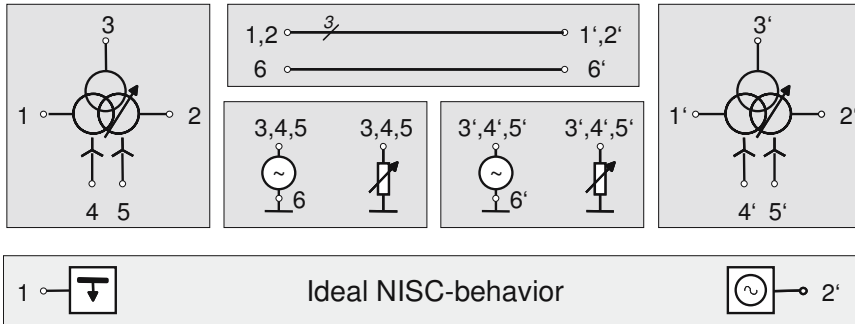


Fig. 9.1. Model of a controllable transmission line with the NISC-approach and underlying building block philosophy

Against this background the NISC-architecture as control philosophy demands a certain amount of controllability. This can be achieved by the FACTS-devices introduced in chapter 1 based on controlled impedances or voltage sources and transformers. In addition special designs could be considered like a four conductor transmission line with symmetry compensation [3] or transmission lines with a certain surge impedance in order to avoid bulk series compensation equipment [4]. Furthermore, controlled series resonance circuits can be added for decoupling the sending and receiving end in terms for short circuit current contributions [5]. As a result the transmission path can be designed according to a building block concept and hence a huge variety of controllers can be created based on the basic FACTS-elements.

9.1.2 Controller Specification

Conventional controller designs for controllable transmission paths demand to incorporate the entire system. In most of the cases this results in a redesign of other network controllers. The controllers should follow the desired functionality independent of hardware configuration of new transmission elements. Easy scalability to different control ranges and flexibility to add ancillary services is required. However, today the number of controlled paths is limited since the control systems cannot cope with potential adverse interaction of these controlled paths. This problem can be overcome by either overall network controllers, which would desire a complete new high-speed network control system. Even in this case the adverse interaction cannot definitely be avoided.

A second approach is to design a controller working for fast actions on local input variables, but achieves coordination through exchange of information with selected parts of the entire system. This reflects the basic requirement for the NISC-architecture. For the realization of such a controller design the following specifications are defined:

- New controller design does not require a redesign of already installed network controllers
- Several network controllers work together with the same control approach
- Robustness according to requirements of power system operation (change of operational points during time periods of days and years)
- Modular controller design for system control and ancillary services; scalable for different control ranges
- No misbehavior in contingency situations

9.2 Architecture

Generally, one has to distinguish between predefined robust controllers for regular operation and contingency situations. In the following the controller for regular operation is referred to the function $\mathfrak{S}_1(\underline{u}_1)$. This function comprises several control algorithms for controlling the transmission path, e.g. active power flow control, reactive power flow control, voltage control, etc. The contingency case is covered by function $\mathfrak{S}_2(x, \underline{u}_2)$. This function affects the regular device control in order to adapt its behavior according to changing network conditions, in particular during contingencies. The overall structure of a NISC controller is shown in Figure 9.2.

In the simplest case the contingency controller does not affect the regular control function. For the initial design of the controller the function of the regular controller can be separated:

$$\mathfrak{S}_2(\mathfrak{S}_1(\underline{u}_1), \underline{u}_2) \equiv \mathfrak{S}_1(\underline{u}_1) \quad (9.1)$$

The design of the regular control function is traditionally based on a thorough network analysis where conventional robust controller design methodologies are applied e.g. H_{∞} [6]-[8]. For practical applications it is hard to get the dynamic system model to design the controller. The effort for this procedure is one reason for the limited use of network controllers in practice. Therefore the controller should be designed more or less independently from detailed system studies for each application. But at first the stability for such designs, independent from their special desired control characteristics, must be ensured.

If the controller has a certain desired characteristic for all operational points, the design can be done once without applying neither structural nor parameter changes during online operation. If not, the controller performance has to be checked in regular intervals and control parameters have to be updated accordingly. Therefore, the connection D_2 (see Figure 9.2) serves as a data channel used for downloading the updated control parameters.

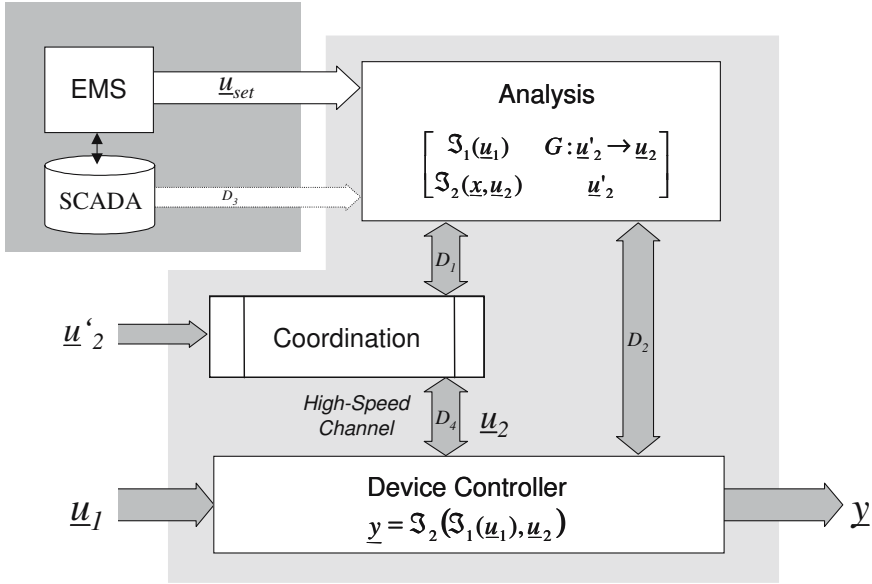


Fig. 9.2. Structure of NISC-Architecture

However from the theoretical point of view, the overall objective of this controller design methodology is to get rid of the connection between controller and SCADA-EMS-System D_3 . The information exchange shall be reduced ideally to the set points $\underline{u}_{set}$ for the network controllers.

The contingency controller supervises the regular controller to prevent it from mal-functioning. This means coordination between the considered controlled transmission path and the entire system. One possible realization is a coordination instance, which derives (from measurement values $\underline{u}_2'$) the contingency case e.g. short circuit, line tripping, outages, overloading, under-voltage, etc. The result is an additional input $\underline{u}_2$ for the device controller upon which the regular control system structure is adapted to the contingency situation.

The coordination is time variant and depends on the actual network parameters and topology. Therefore the proposed NISC-architecture is despite its functional similarity not directly belonging to the class of adaptive controllers. The major difference lies in the mapping $G: \underline{u}'_2 \rightarrow \underline{u}_2$, which defines what kind of measurement quantities are mapped on which additional input quantity for the device controller (see Figure 9.2). In particular in comparison to centralized real time network control systems, within this approach the amount of high speed data transmission is drastically reduced. No additional broadband SCADA-system is needed for the realization. However a certain exchange of data for online coordination of contingency cases cannot be avoided. Future optimization potential of the NISC-architecture lies in totally reducing the high speed data channel by sub-

stituting the coordination instance with a special signal processing unit on the device level. The major task of this signal processing unit is to establish a mapping

$$H : \underline{u}_1 \rightarrow \underline{u}_2 \quad (9.2)$$

and thereby deriving the contingency case out of locally available measurements.

In conclusion the ideal NISC-architecture shall concentrate all high-speed data processing, measurement and reaction schemes at the device level. Slow processes and methodologies are placed on the system level.

9.2.1 NISC-Approach for Regular Operation

The non-intrusiveness will be explained in the following according to Figure 9.3. The NISC-approach ensures that there are no new instability regions due to adding a new component.

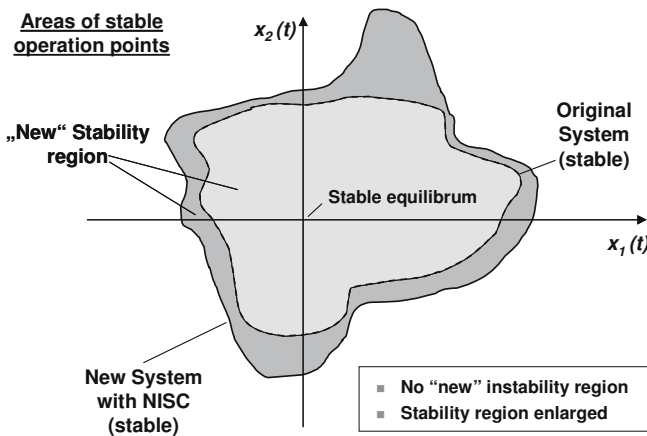


Fig. 1.3. Areas of stable operation points enlarged by adding new controllers with NISC-approach

The ideal goal of the NISC control design is to avoid the frequent update of the controller while ensuring certain robustness. There are several approaches possible to realize such a controller for the standard function of controlling the power flow or the voltage with the additional network element.

The first approach is coming from the theory of passivity. If a stable power system without the new controllable device is assumed, the system is passive if an energy function $V(T)$ exists for time points $T \geq 0$ [9].

$$V(T) \leq V(0) + \int_0^T y(t)u(t)dt \quad \forall u(\cdot), T \geq 0 \quad (9.3)$$

If the additional network controller fulfills the same requirement and is also passive, then both systems in parallel or in a feedback loop are also passive and therefore stable. This means, that the additional component does not affect the stability itself if there is no energy input from this system. For the normal operation of fixing an operational point this is sufficient, but this approach does not tell anything about the damping of the resulting system. Also for additional components with storage characteristic this is not applicable.

Another nearly similar approach is the Controlled Lyapunov Function (CLF) for a system with the structure:

$$\dot{x} = f(x, u) = f_0(x) + \sum_{i=1}^m u_i f_i(x) \quad (9.4)$$

If the power system without control input is stable, it can be shown that there exists a positive energy function $V_{PS}(x)$ with $\dot{V}_{PS} \leq 0$. The system with the network controller is stable if, when V_{PS} is combined with the energy function of the controllable element V_{CO} , the resulting function V is a Lyapunov function for the new system. This holds if:

$$\dot{V} = \dot{V}_{PS} + \dot{V}_{CO} \leq \dot{V}_{CO} \leq 0 \quad (9.5)$$

In [10] this is shown with the example of a controllable series device. It is shown that the stability area of the resulting system is enlarged by adding the new component. To get an improved damping characteristic is a question of the controller design. The resulting controller must be checked to fulfill the above requirements for CLF. The results so far are adaptable for the basic control function. The robustness of the controller depends on the model of the device and is independent from the system's model so far the system can be assumed to be stable. Therefore a robust control design is desired.

To design a robust controller for specific characteristics it is desired to make the design based on a typical structural environment and not with a detailed system study. An approach for such a design is shown in [10] where the structure of the system is known, but not the exact parameter values.

With these approaches within the NISC-architecture a redesign of the controller can be avoided and the stable operation together with other controllers can be guaranteed. The stability is guaranteed and the robustness depends only on the device model. As a result the area of stable operation points remains the same after integrating a new controlled transmission path, which adds stable operation points.

9.2.2 NISC-Approach for Contingency Operation

The major difficulty for the application of network controllers is that it must be assured that they behave correctly during abnormal operation situations or contingency cases. In particular this is required for all kinds of fast controlling devices and therefore especially FACTS-devices. Many application studies have shown that the technical advantages of e.g. power flow controllers can only be profitably

utilized in connection with a purposeful extension of the control and protection system. The critical factor is the dynamic behavior of the power system. This gets worsened and furthermore an overall endangering of the steady-state and dynamical system security is expected if the operation of network controllers like FACTS-devices are not coordinated properly.

The coordination has to be done according to changing operating situations or critical events in the power system. The NISC-architecture solved this problem due to its preventive coordination mechanism. This control is activated by a trigger signal reflecting a contingency event in the entire system. This broadcast activates the according local contingency control method within the device controllers (see Figure 9.4). After the contingency has been cleared the device controllers request a new planning and download cycle since the network topology or operation condition could have changed.

The analysis of the contingency cycle-time and the regular cycle-time shows that an online coordination of several network controllers cannot be achieved.

$$\Delta T_{CC} \ll \Delta T_{CR} \quad (9.6)$$

To implement a full dynamic system analysis online is not possible due to the centralized databases and analysis time effort. Therefore the underlying concept of coordination is referred to as preventive coordination since the coordination is done before execution starts.

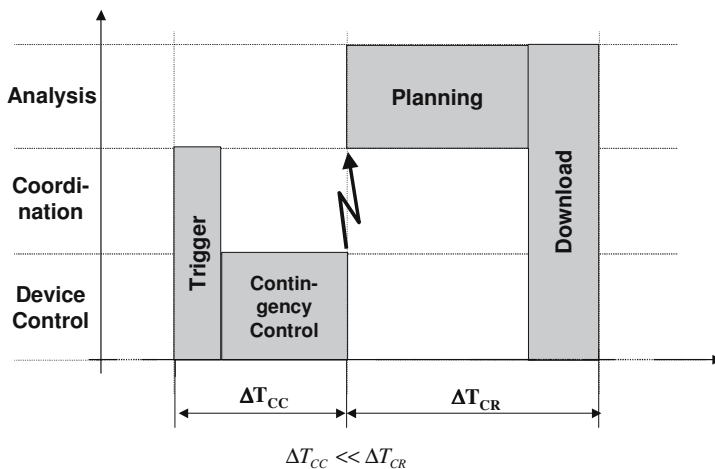


Fig. 9.4. Typical contingency control cycle within the NISC-architecture

This chapter has specified the requirements for fast network controllers especially FACTS-controllers. In particular power flow controllers require a coordinated approach, because of their interaction with wide parts of a power system. Adding FACTS-controllers shall always improve the stability of a system for all expected operations. Designs for regular and contingency operations can be sepa-

rated. To be prepared for a contingency operation a analysis and planning phase has to be performed in cycles. The action schemes needs to be downloaded into the local controller. The controller is not prepared to act in contingency situations according to the pre-defined schemes. The required data are ideally locally available or need to be transmitted from pre-selected source in the system. The following chapters will show implementation examples for specific applications of this basic NISC-architecture.

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